An Engineering Test Facility for Heavy Ion Fusion – Options and Scaling *

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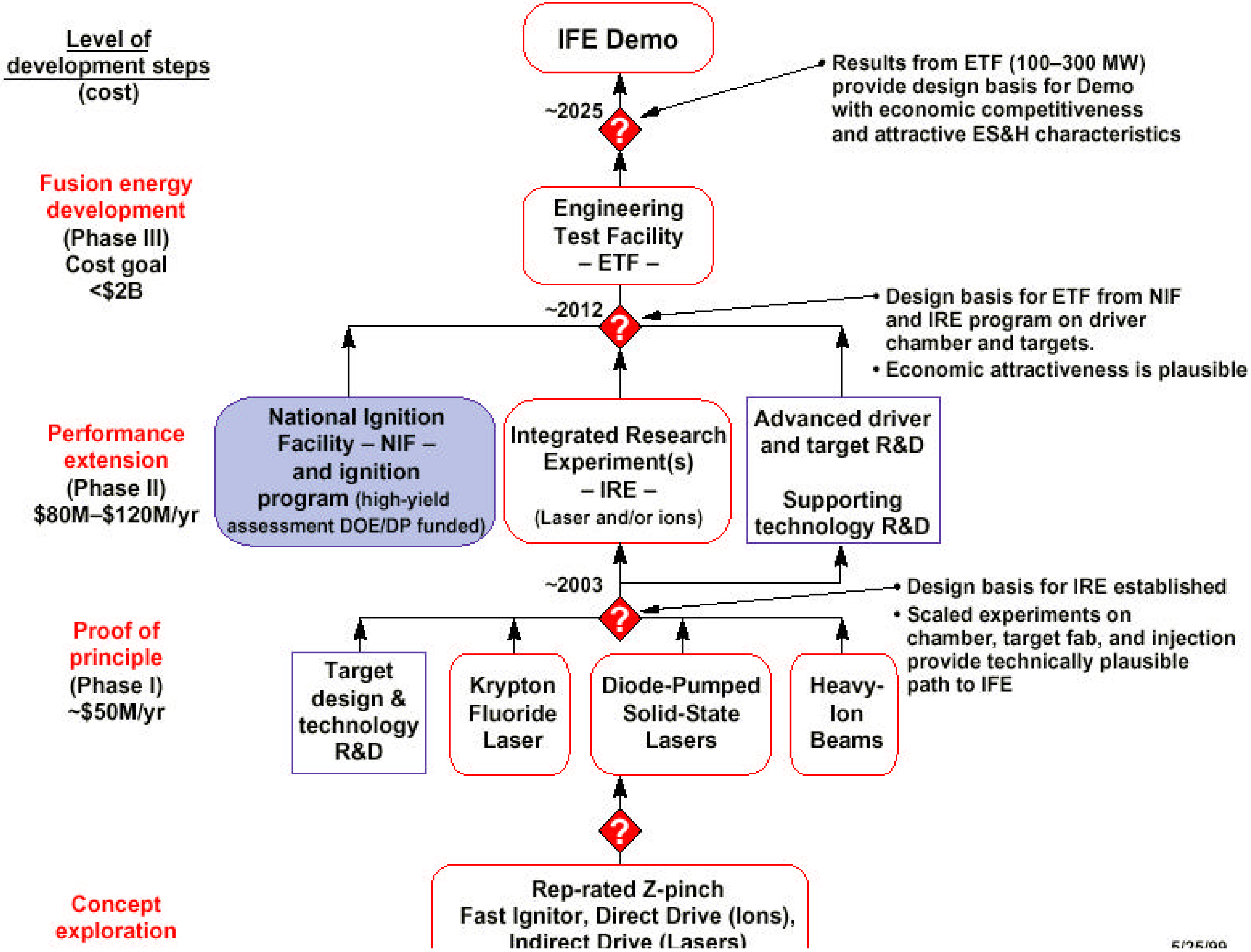
The Inertial Fusion Development Strategy is integrated with the Fusion Energy Road Map



Objectives of the ETF

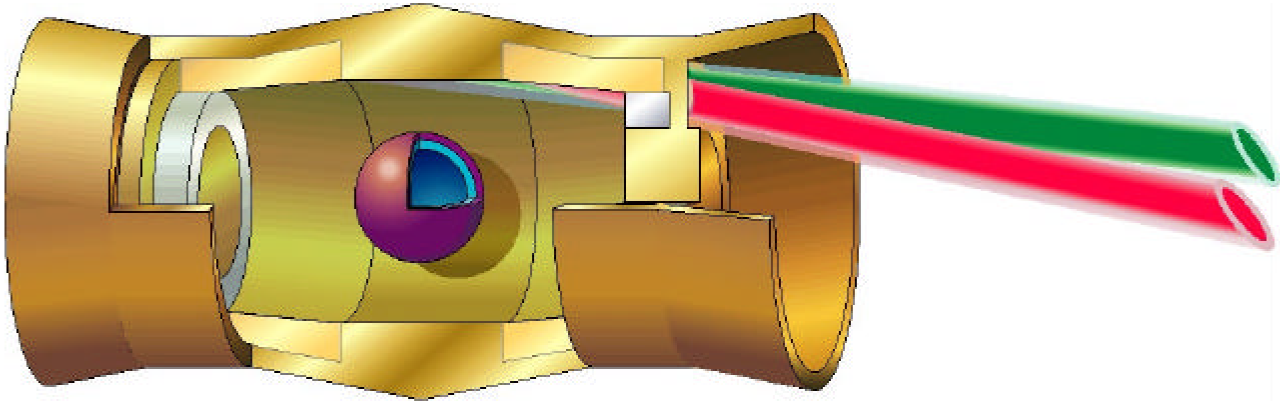
- **System Integration** – Integrate all the major subsystems required for an inertial fusion power plant (driver, targets, fusion chamber, and heat removal system)
- **Target Gain and Yield**– Demonstrate target gain high enough for attractive economics (> 40 for a 25% efficient driver). Maximize yield in single shot tests (e.g., Y > 100 MJ may be possible with 2 MJ driver).
- **Driver** – Demonstrate driver technology with efficiency needed for economical power, including beam steering and propagation through post shot chamber conditions
- **Chamber & Nuclear Technology** – Operate at rep-rate with reduced yield (and thus power) to investigate chamber dynamics; demonstrate recovery between shots; radiation damage testing
- **Target Fabrication and Injection** – Demonstrate high rep-rate production (scalable to low cost), target injection and tracking
- **Heat Transfer and Other Plant Systems** – Demonstrate HTS, steam generation, electricity production(?), and safe operation including recovery of tritium.

ETF will progress through a series of increasingly difficult tests

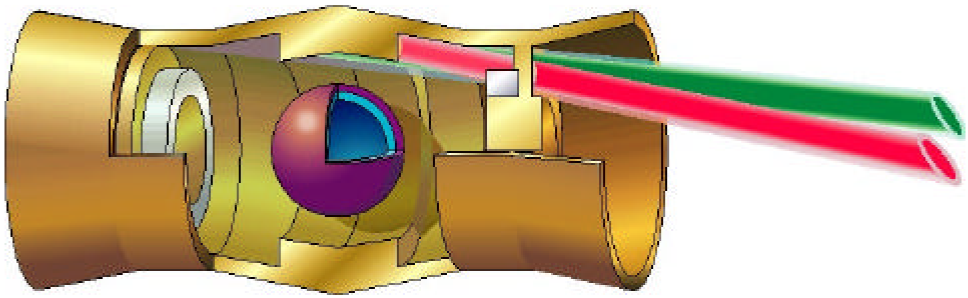
- High rep-rate driver operation with required efficiency
- Single shot, high gain target experiments to optimize target designs
  - first demonstration for heavy ion driver
- Short duration (minutes), burst mode tests at low yield to prove and optimize chamber designs
  - tritium breeding not required
  - batch production of targets
- Steady state, average power tests for days/weeks/months
  - automated target production
  - include tritium breeding and recovery
  - include heat removal and steam generation
  - produce electricity?
- Upgrade driver and plant components to demo scale?

Distributed radiator target designs have been developed at LLNL

Standard hohlraum-to-capsule radius ratio design (HCR = 2.1)

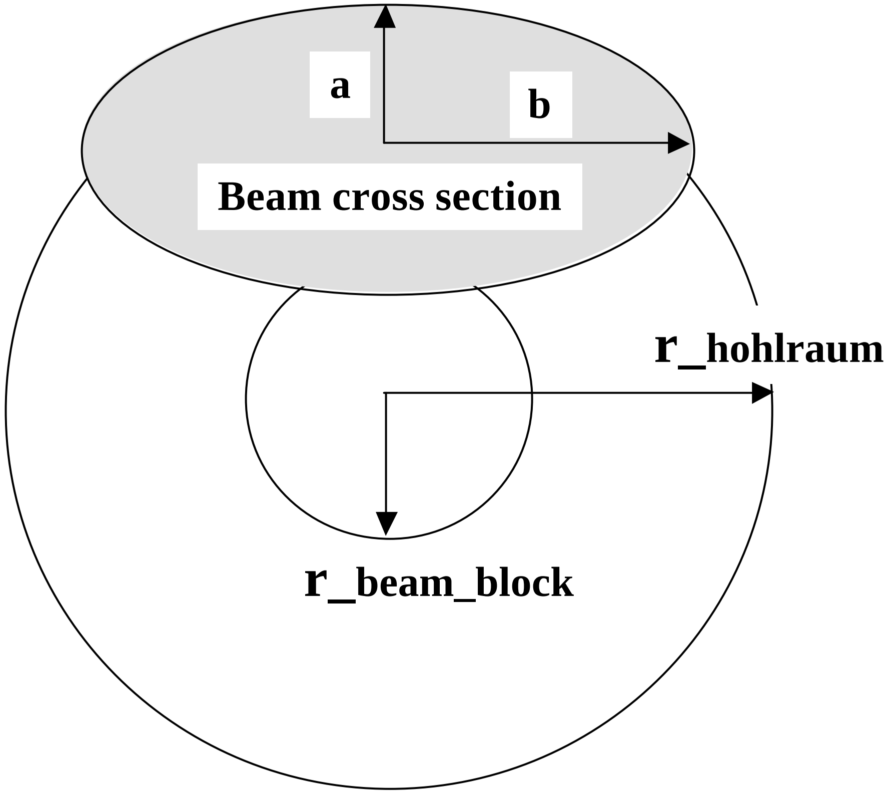


Close-coupled design (HCR = 1.6)



Hohlraum is smaller – requires smaller beam spot size

Beam spot size requirements vary with capsule radius and hohlraum-to-capsule radius ratio

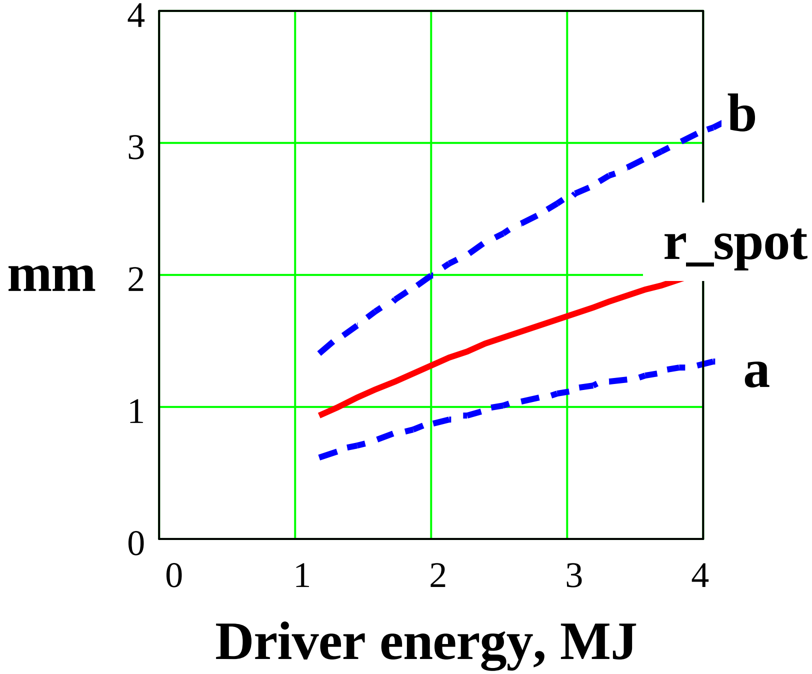


End view of target showing how beams are positioned (one of many shown)

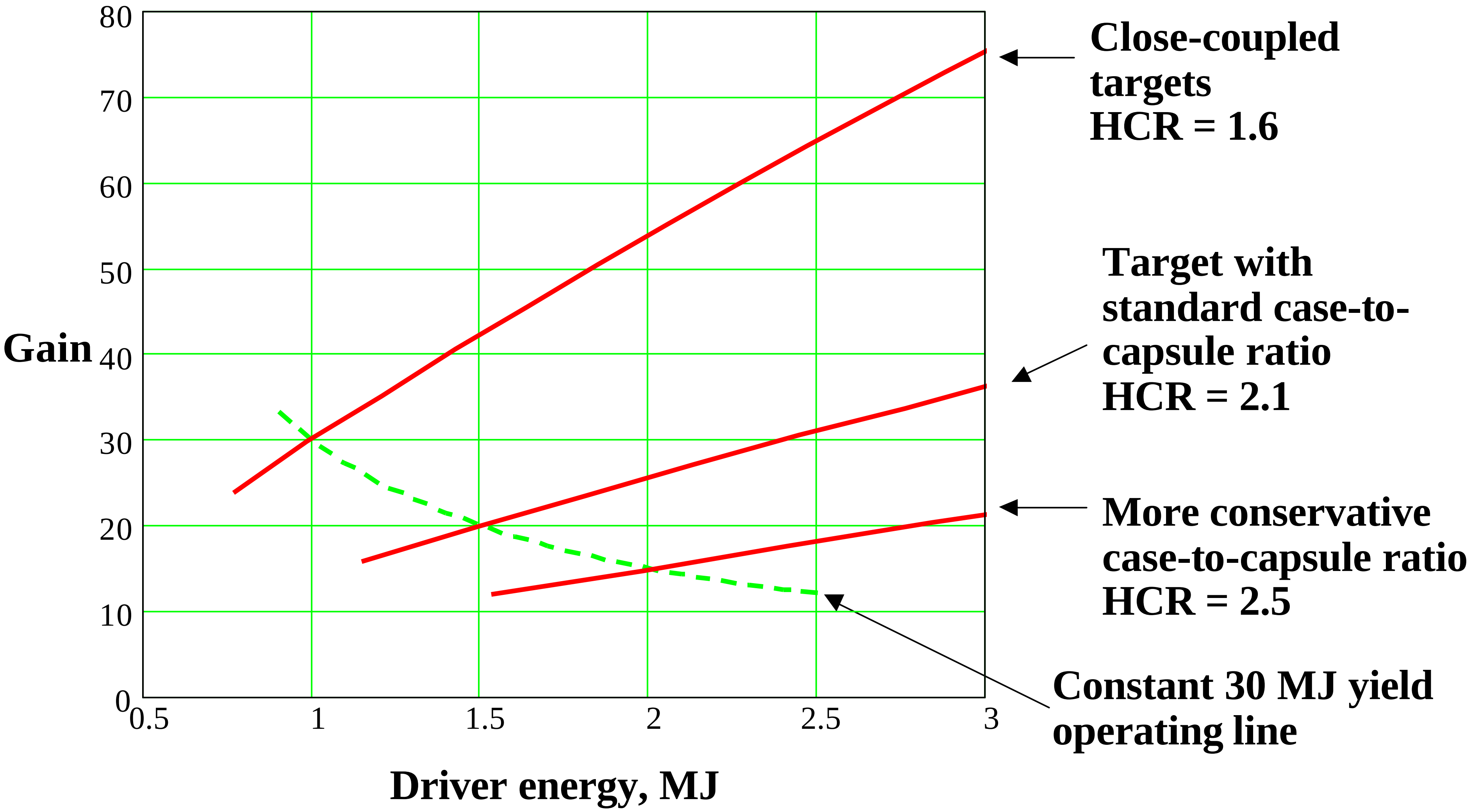
Effective beam spot size =

$r\_spot = (a^2 + b^2)^{1/2}$

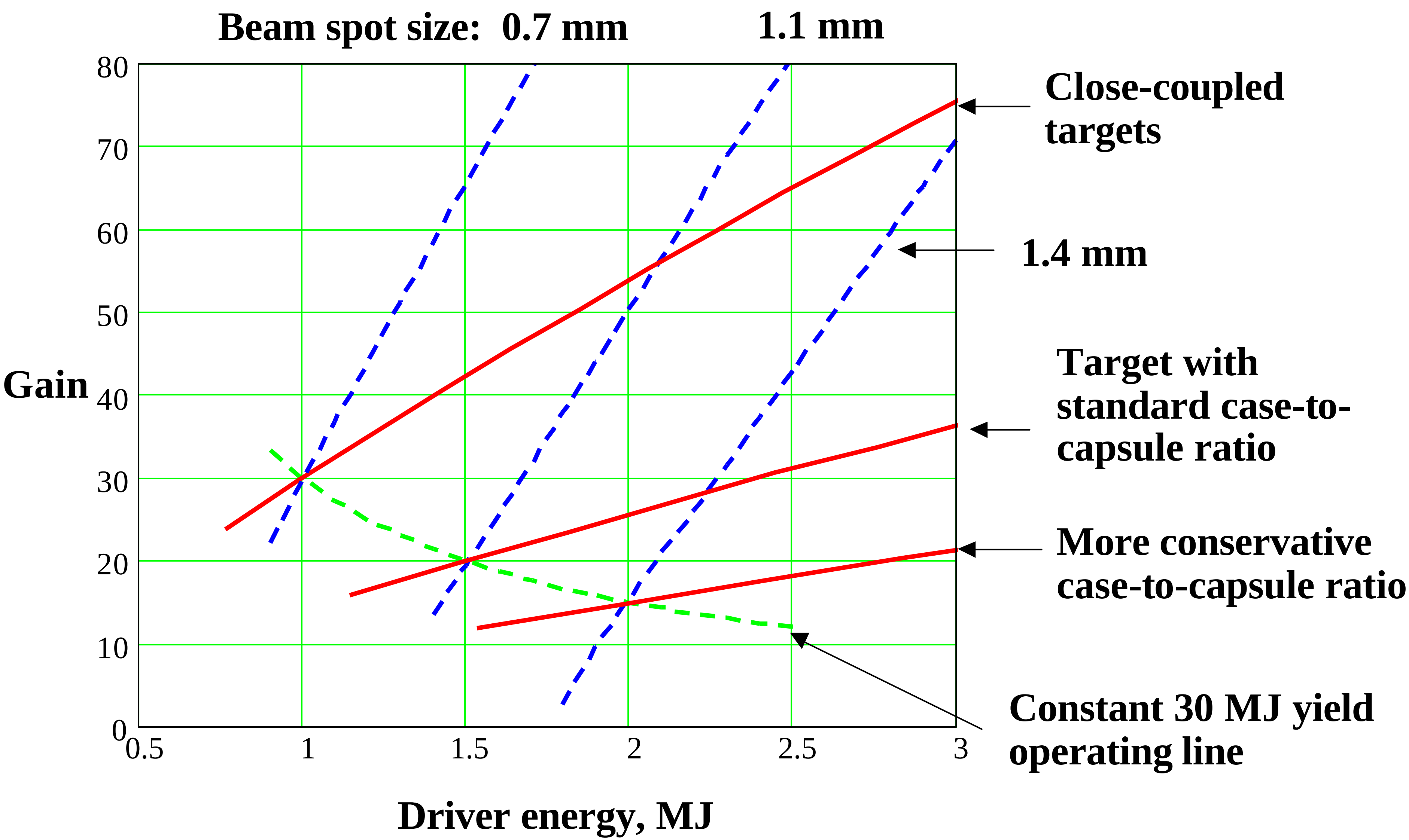
Beam spot dimensions for standard target (HCR = 2.1)



Target gain for different hohlraum-to-capsule ratio (HCR) designs



Driver energy and focusability will limit range of targets that can be investigated



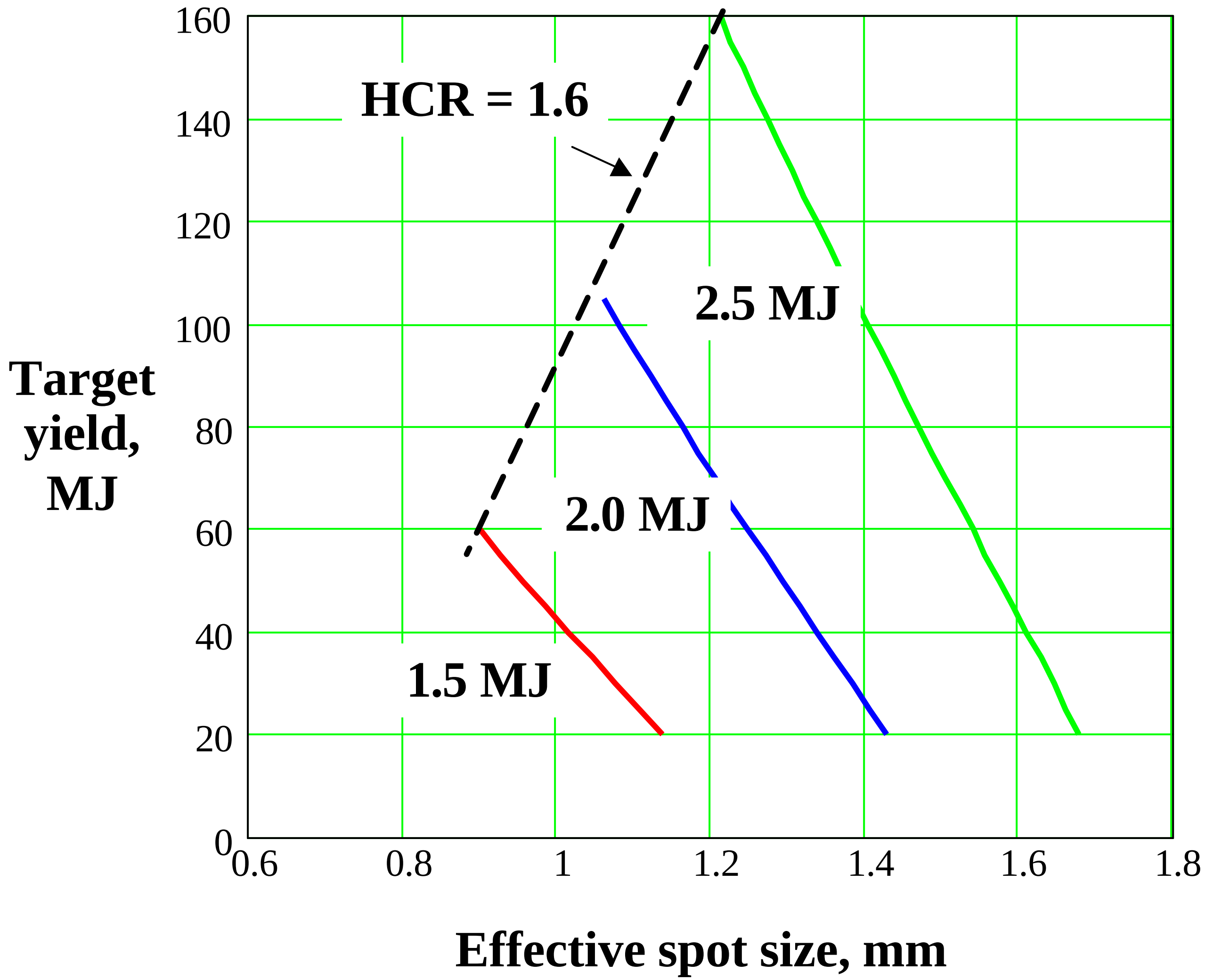
Target scaling issues

- Desirable to map out a significant part of target gain versus driver energy space, but capital costs will likely limit total available driver energy

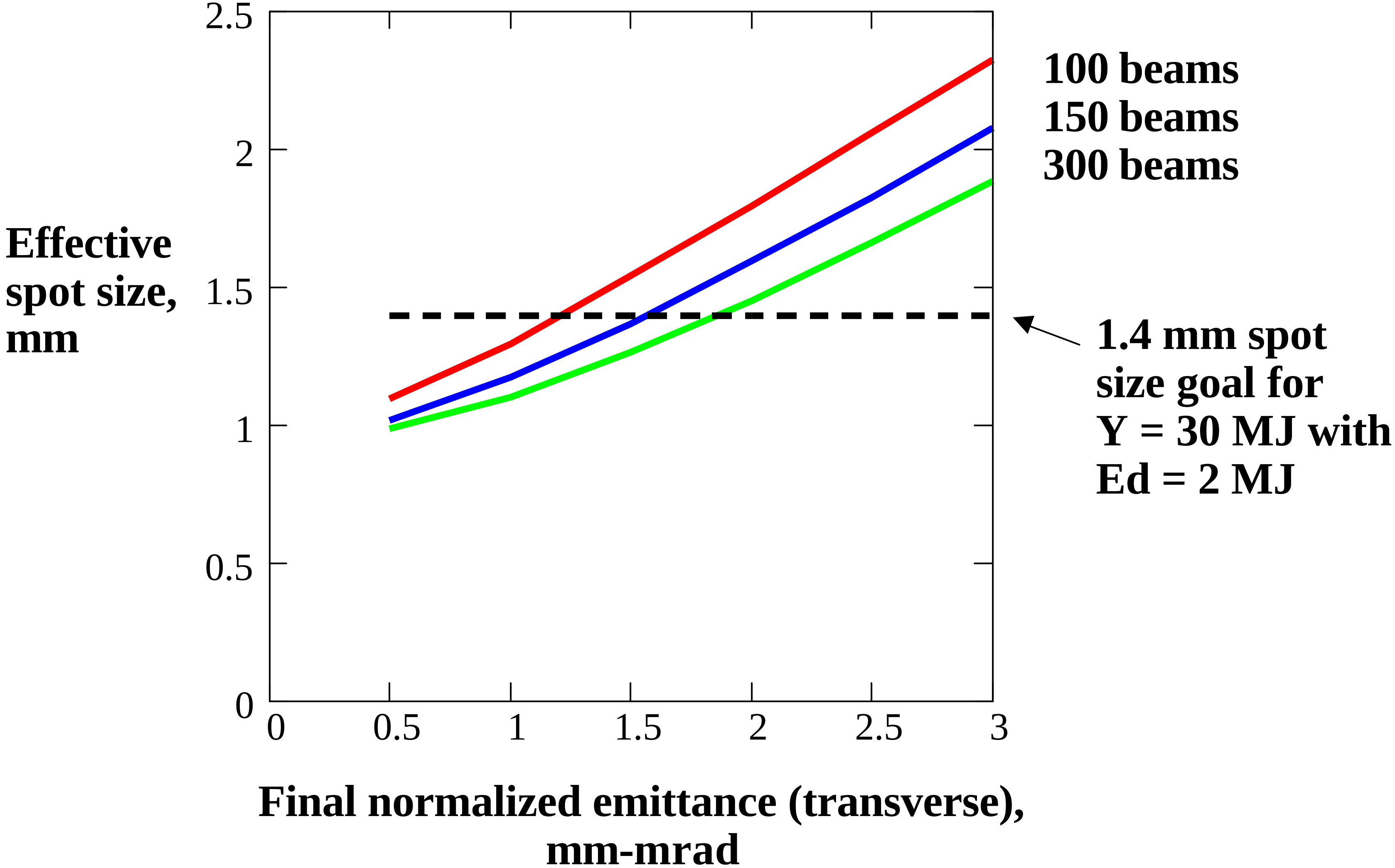
- Power handling costs also favor lower yield targets, but low yield targets require small beam focus spot sizes (shorter final focus length for ETF helps somewhat)

- Smaller targets require capsules with better surface quality than full size targets, thus requiring production capabilities exceeding commercial power plant scale

Achieving small spot size is required for higher yields with a given driver size

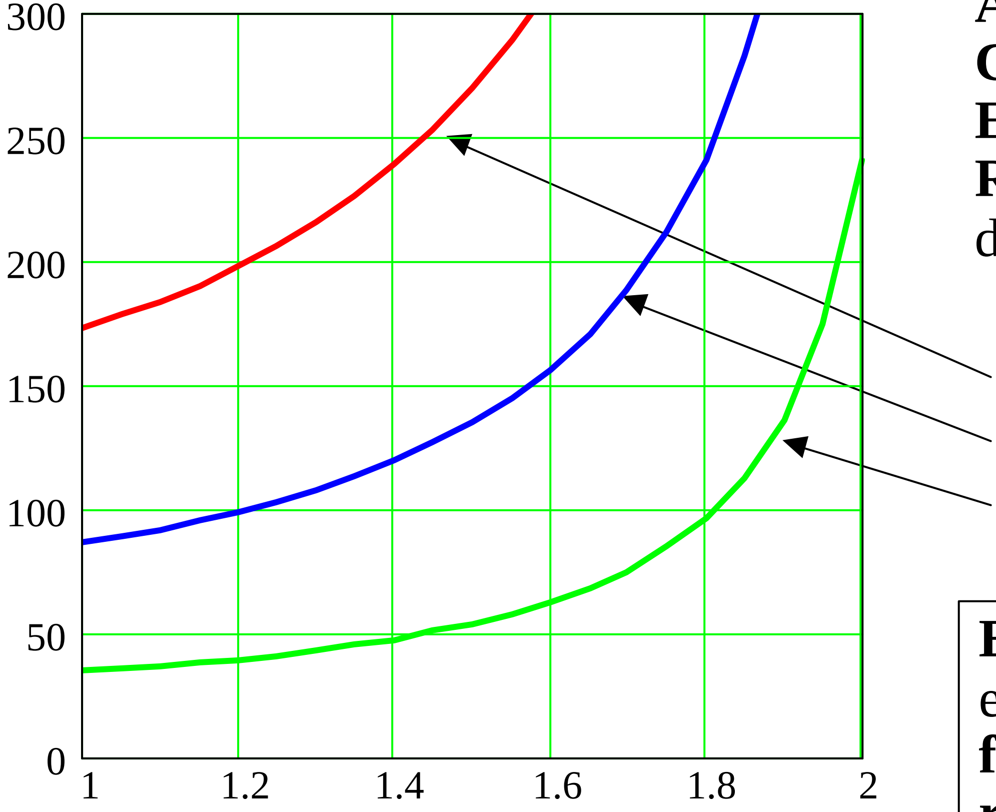


Maintaining beam quality is key factor in achieving small spot sizes



Relationship between number of beams, emittance and neutralization for a given spot size

Number of beams



Final normalized emittance (transverse), mm-mrad

Assumes
Cs^{+1}
Ed = 2 MJ
Rspot = 1.4 mm
dP/P = 0.1%

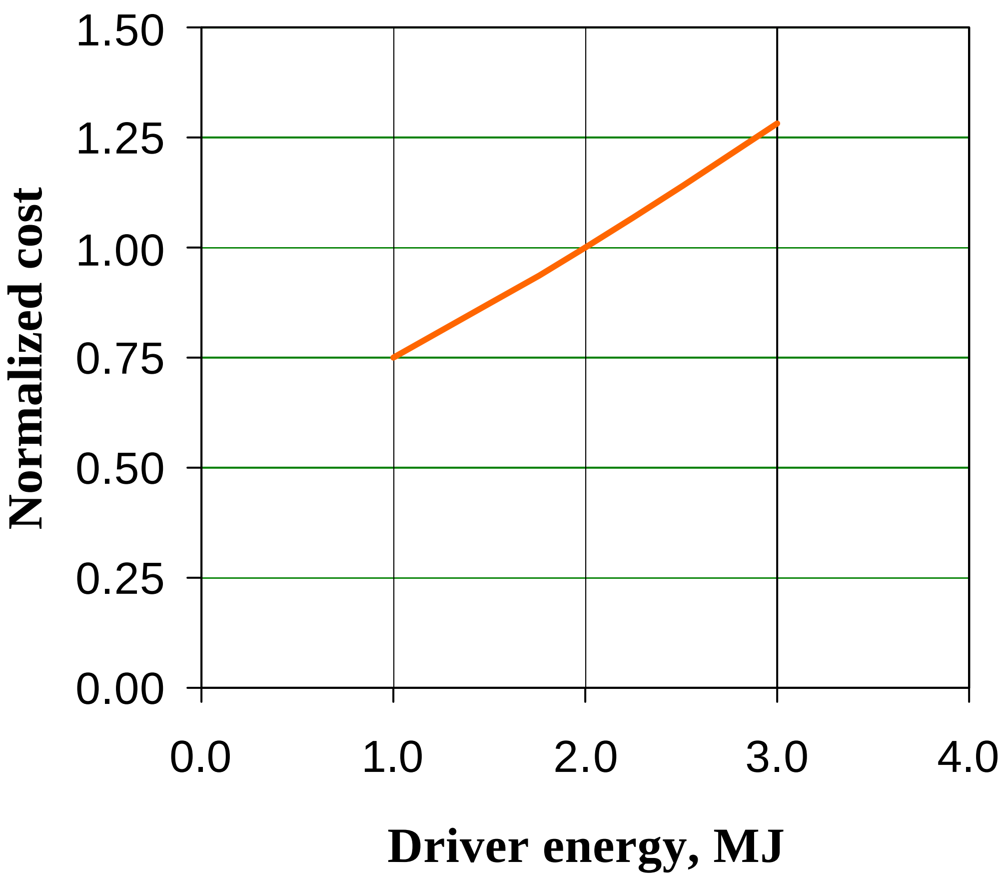
Neutralization:
90%
95%
98%

Example:
e_n =1.6 mm-mrad
f_n = 95% neutralization
requires ~ 160 beams

Driver scaling considerations

- To achieve small spot sizes required by reduced scale targets requires
  - Many beams (> 100)
  - Short initial pulse duration (< 4 ms) to keep chromatic aberrations small
  - High degree of neutralization (>95%) prior to final transport to keep space charge effects small
  - Short final focus magnets (< 0.5 m) with fields ~ 5 T to keep geometric aberrations small
- Driver efficiency will be comparable to full scale driver (~ 35% for 2 MJ, 160 beam, Cs^{+1} case)
- Near full scale driver technology will be demonstrated (compact quad arrays, large induction cores, acceleration to full ion energy, etc.)

Driver costs scaling with driver energy



- **Relatively high buy-in cost: reducing Ed by 50% to 1 MJ reduces cost by ~ 25%**

- **Favorably scaling to higher energy: increasing Ed by 50% to 3 MJ increases cost by ~28%**

ETF chamber dimensions and rep-rate are chosen to reproduce key phenomena

- **Geometric scaling**
  - Key variable is target yield, Y
  - Chamber, target injection, and driver/chamber interface dimensions reduced by a factor L
  - L scaling with Y chosen to optimally match different key phenomena
  - Some dimensions can be adjusted to improve fidelity (e.g. magnet standoff)
- **Millisecond phenomena**
  - Liquid/target motion: preserve relative effects of inertia and gravity
    - » Liquid/target velocities scale with $L^{0.5}$
    - » Repetition rate scales with $L^{-0.5}$
    - » Preserves liquid and target trajectories
  - Condensation on droplet sprays
    - » Droplet number density adjusted to preserve droplet heating (ΔT)

Key phenomena (cont.)

- **Microsecond phenomena**
  - X-ray ablation and debris venting
    - » Impulse loading effect on liquid trajectory ($L \sim Y^{0.24}$)
    - » Ablation layer thermodynamics and hydrodynamics ($L \sim Y^{0.5}$)
    - » Pocket energy density / coolant heating ($L \sim Y^{0.33}$)
  - Neutron-heating induced liquid motion ($L \sim Y^{0.4}$)
- **Nanosecond phenomena**
  - Target output x-ray and neutron spectra/deposition
    - » Lower capsule ρr shifts more energy to neutrons (good)
    - » X-ray/debris energy partition tuned to adjust ablation mass
  - Target/beam physics
    - » Most target/beam studies occur in single-shot chamber where initial conditions easily controlled and measured and diagnostic access is easier

Key phenomena (cont.)

- **Quasi-steady phenomena**
  - Tritium and heat recovery/chemistry control
    - » Use single loop, full height, scale flow area with fusion power
    - » Adjust secondary blanket thickness to preserve tritium breeding
  - Chamber thermal response
    - » Thermal stresses scale linearly with volumetric heating and L^2
    - » Magnet standoff tuned to give acceptable magnet heating and target illumination geometry
  - Chamber damage (activation/corrosion)
    - » Scaling accelerates damage due to increased fluence / coolant temperature)

Chamber dynamics can be investigated at reduced scale

- For thick liquid wall chambers, there are a variety of non-dimensional parameters to scale various effects (e.g, surface flux, impulse loading, neutron induced motion)

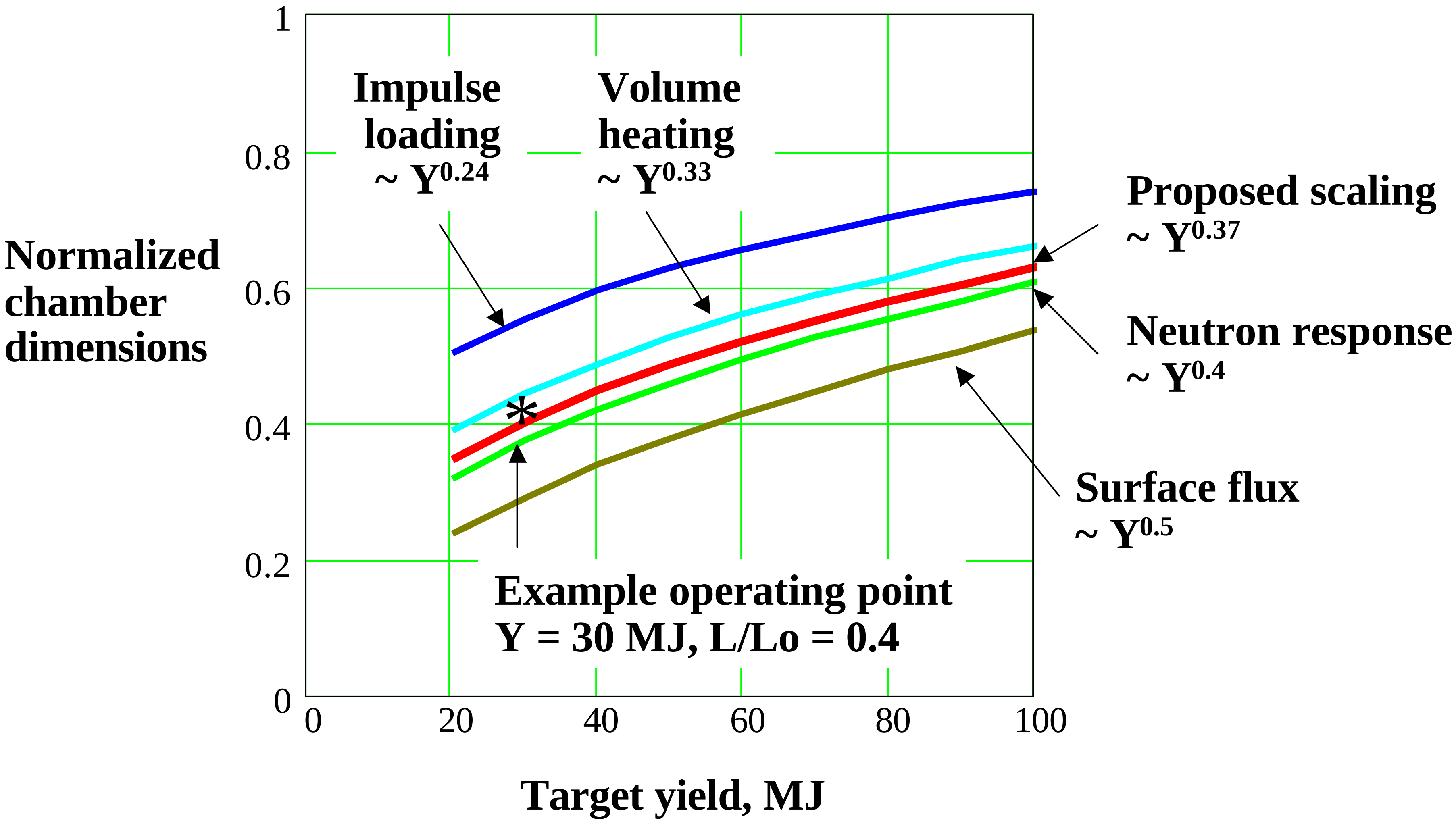
- Scaling as $(\text{yield})^{0.37}$ is proposed. The 0.37 scaling coefficient is midway between the 0.24 needed to preserve impulse loading and 0.5 needed to preserve debris induced thermodynamics and is close to the 0.4 needed to preserve neutron induced motion.

- For a 30 MJ ETF, all dimensions are reduced by

  $L/Lo = (30/350)^{0.37} = 0.4$

- By varying the target yield about this design point, different chamber dynamics effects can be more closely matched

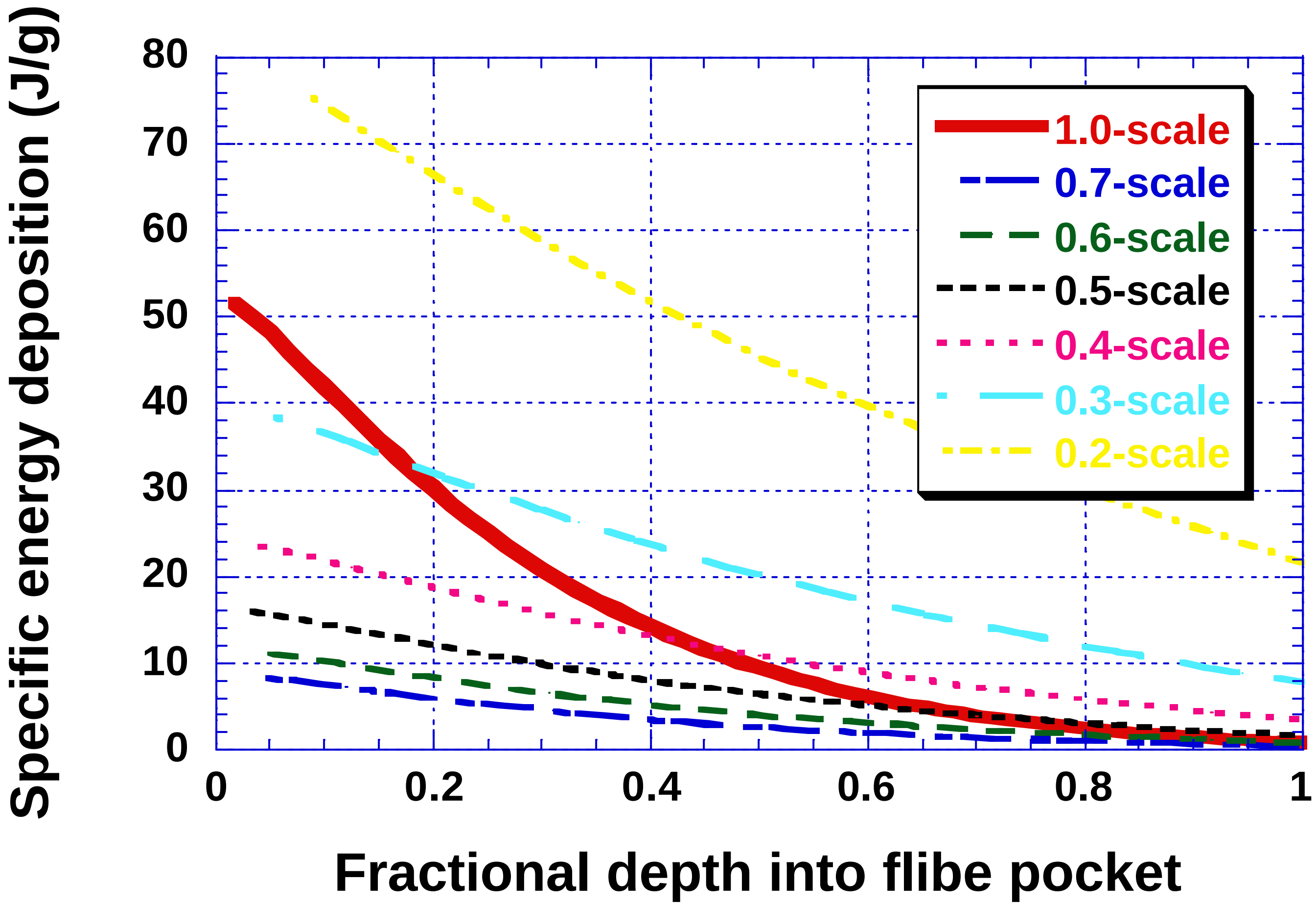
Chamber scaling with target yield to match various effects



Comparison of key nuclear parameters

	ETF	Power Plant
Yield, MJ	30	350
Rep-rate, Hz	9.5	6.0
Fusion power, MW	285	2100
Thermal power, MWt	335	2480
Capacity factor	50%	80%
1st wall radius, m	1.2	3.0
1st wall annual fast n^o fluence (> 0.1 MeV), n/cm^2-y	1.3×10^{22}	1.6×10^{21}
1st wall heating, W/cm^3	166	37
TBR (pocket/total)	0.55/1.23	1.18/1.26
Magnets heating in coils, mJ/cc per shot	0.46	0.07
Magnet annual fast n^o fluence (> 0.1 MeV) to coils, n/cm^2-y	1.5×10^{18}	4.1×10^{17}
Magnet annual dose, MGy/y	64	1.5
Estimated magnet lifetime, years of operation	1.6-6.7	24-66

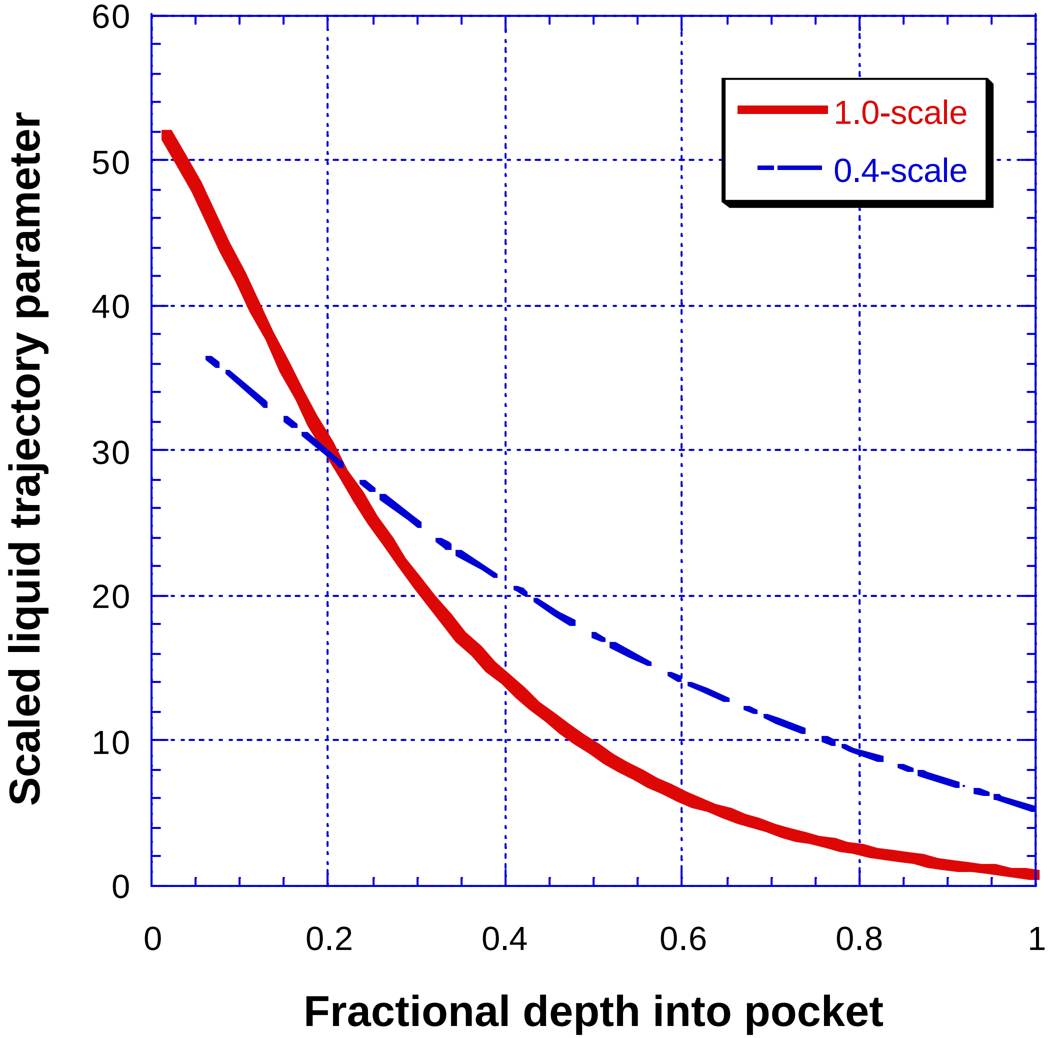
ETF will provide first test of neutron induced chamber effects



1.0 scale is for 350 MJ

All others at 30 MJ

Neutron induced liquid motion for 0.4 scale chamber compared to full scale

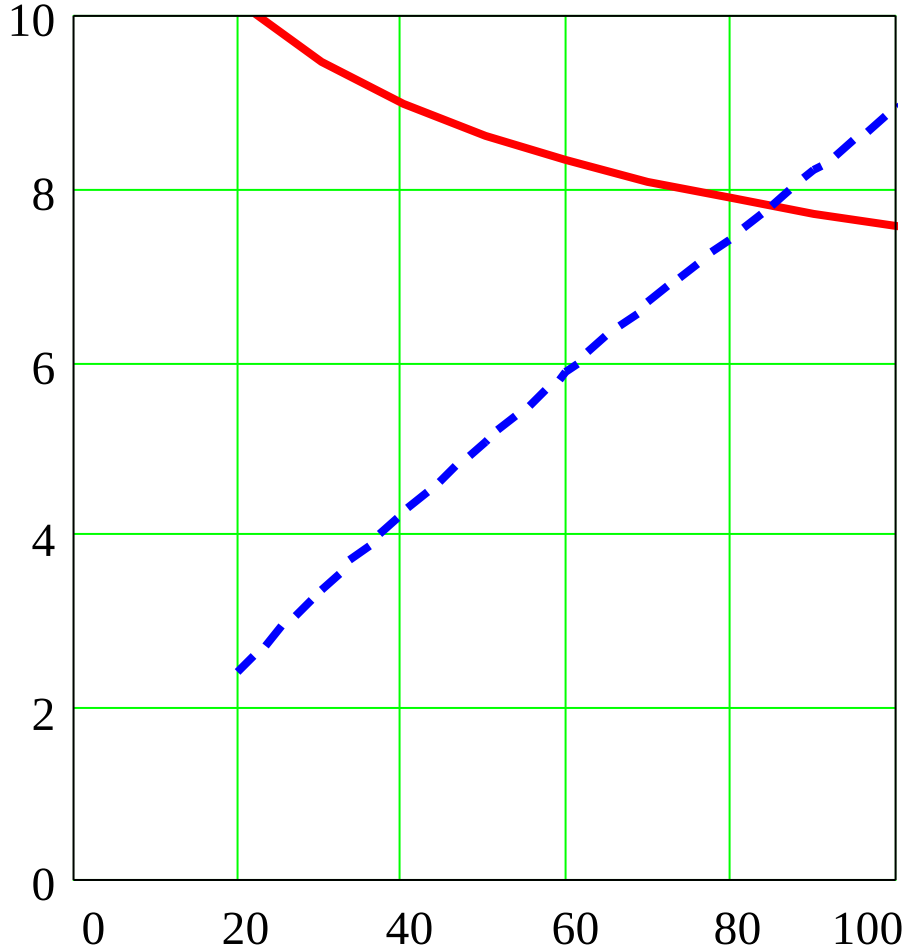


Scaled parameter is (J/g) divided by jet velocity:

~ (J/g) / $L^{0.5}$

Rep-rate and thermal power are determined by geometric scale

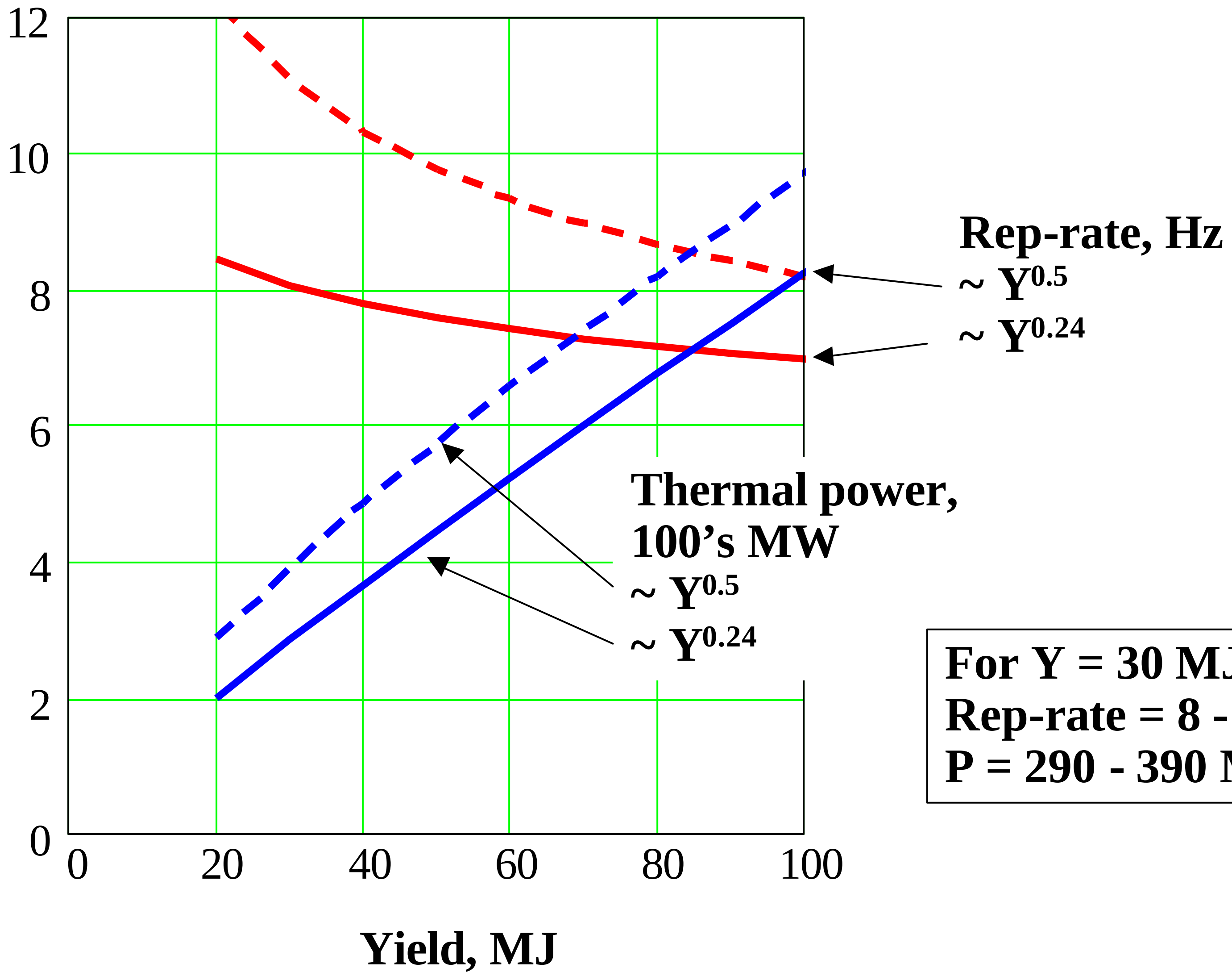
Results for $Y^{0.37}$ scaling



Yield, MJ

Example:
Y = 30 MJ
L/Lo = 0.4
Rep-rate = 9.5 Hz
Power = 335 MWt

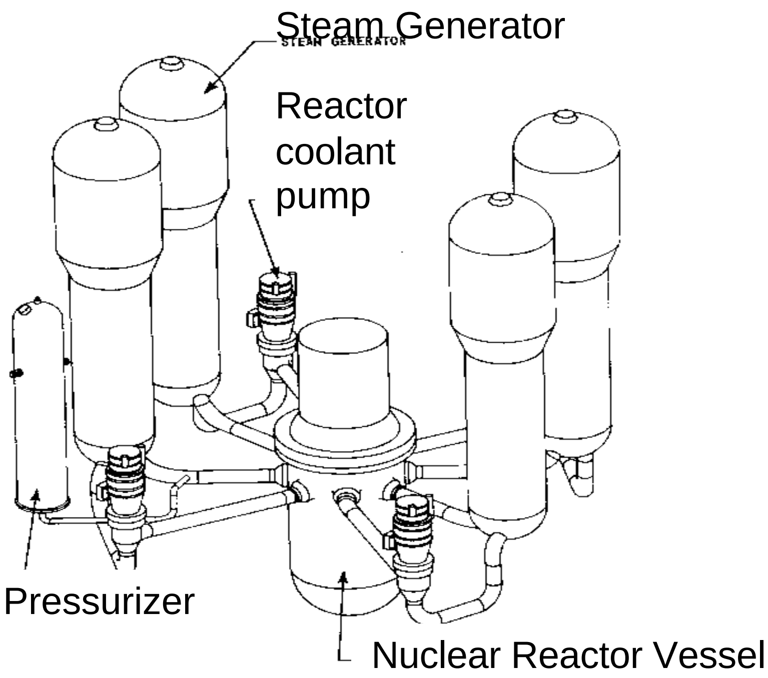
Rep-rate and power are not very sensitive to choice of scaling exponent



For Y = 30 MJ
Rep-rate = 8 - 11 Hz
P = 290 - 390 MWt

Heat transfer components can be tested at near ½ scale

- Power plants typically have 2-4 heat transfer loops
- Assuming a 2500 MWt four loop design gives 625 MWt each
- ETF can test a single loop at 335 MWt or ~ ½ commercial scale
- Full length steam generator with fewer tubes will be used to preserve boiling effects.



Westinghouse 4-loop reactor coolant system

Target fabrication and injection system requirements will be demanding

- Target fabrication requirements will range from single-shot tests to batch mode to steady production
- Rep-rate and surface quality requirements will exceed commercial systems because capsules are smaller
- Because chamber scaling preserves the relative effects of inertia an gravity, the scaled targets will follow the same scaled injection trajectory, and the precision at shorter length should improve.
- Target size scaling with yield ($Y^{0.34}$) is close to chamber/ injector scaling $Y^{0.37}$

Example parameters for different driver energies and yields

Driver energy, MJ	2			3		
Yield, MJ	30	80	100	30	120	200
Gain	15	40	50	10	40	70
HCR	2.5	1.8	1.6	3.1	2.0	1.6
Spot size, mm	1.4	1.2	1.1	1.9	1.6	1.4
Chamber scale	0.40	0.58	0.63	0.40	0.67	0.81
Rep-rate, Hz	9.5	7.9	7.6	9.5	7.3	6.7
Power, MWt	340	750	900	340	1040	1580

Low yield, Gain = 40 demonstration, Maximum yield for CCR = 1.6

The ETF is a key step in heavy ion fusion development

- Desirable to operate at small scale (e.g., E ~ 2 MJ, Y ~ 30 MJ) for rep-rate tests to contain costs
- To access this operating space requires:
  - Target gain > 15 with small capsules (but larger than NIF)
  - Beam focusing to small spot size (< 1.4 mm)
  - Target production at higher rep-rate (~9.5 Hz) and precision than commercial systems
- The ETF will provide flexibility in developing HIF
  - Beam switching to multiple chambers (single shot and high rep-rate)
  - High yield (~ 100 MJ) tests and high rep-rate tests
  - Ability to varying target yield by varying target design (e.g., case-to-capsule ratio, tritium loading) and/or driver energy
- The ETF will define the path to Demo